# Amplified Arctic climate change: What does surface albedo feedback have to do with it?

Michael Winton

Geophysical Fluid Dynamics Laboratory/NOAA

Submitted to *Geophysical Research Letters*

4 October 2005

---

Corresponding author: Dr. Michael Winton, GFDL/NOAA, P.O. Box 308, Princeton University Forrestal Campus, Princeton, NJ 08542. email: Michael.Winton@noaa.gov

## Abstract

A group of twelve IPCC fourth assessment report (AR4) climate models have Arctic (60N-90N) warmings that are, on average, 1.9 times greater than their global warmings at the time of $CO_2$ doubling in 1%/year $CO_2$ increase experiments. Forcings and feedbacks that impact the warming response are estimated for both Arctic and global regions based on standard model diagnostics. Fitting a zero-dimensional energy balance model to each region, an expression is derived that gives the Arctic amplification as a function of these forcings and feedbacks. Contributing to Arctic amplification are the Arctic-global differences in surface albedo feedback, longwave feedback and the net top-of-atmosphere flux forcing (equal to the sum of the surface flux and the atmospheric heat transport convergence). The doubled $CO_2$ forcing and non-SAF shortwave feedback oppose Arctic amplification. SAF is shown to be a contributing, but not a dominating, factor in the simulated Arctic amplification and its intermodel variation.

# I.  Introduction

Polar amplification of $CO_2$ forced warming is a common feature of climate change simulations.  In transient simulations, southern hemisphere warming is retarded by the large heat uptake of the southern ocean, leaving the Arctic as the global location with the largest warming.  This aspect of the global warming pattern has often been linked to surface albedo feedback (SAF) – the extra absorption of shortwave radiation as ice melts and the surface becomes less reflective.  It is the goal of this paper to place the SAF in the context of other feedbacks and forcings that affect Arctic amplification.

Important work on this topic was done by Hall (2004) who showed, by disabling SAF in the GFDL climate model, that it accounts for part but not all of the polar amplification.  Vavrus (2004) performed similar experiments with the GENESIS2 climate model to evaluate the role of cloud changes under doubled $CO_2$.  He found that the cloud fraction changes enhanced the warming at all latitudes but by a fractionally greater amount in the Arctic, therefore enhancing Arctic amplification.  The high-latitude response to increased $CO_2$ was found to be quite variable amongst the group of 15 CMIP climate models studied by Holland and Bitz (2003).  Using correlations, they identified a number of processes that contributed to the variation of Arctic amplification amongst the models.  They found that models with larger increases in ocean heat transport, larger increases in cloud cover, and thinner control climate sea ice tended to have larger Arctic amplification.  They proposed that thinner sea ice would lead to an increased ice-albedo feedback.  However, Flato (2004) found that in the southern hemisphere, thinner ice was associated with reduced warming in the CMIP models.  In the southern hemisphere, Flato (2004) found some tendency for models with more extensive ice to produce greater warming while in the northern hemisphere there was a tendency toward the opposite relationship.  These studies emphasize the complexity of Arctic amplification and the multiplicity of processes that contribute to it.

In this paper the conventional energy balance method of global climate sensitivity analysis is applied to both global and Arctic regions. A comparison is then made of the impact of differences in the forcings and feedbacks of the two regions. The simulations analyzed come from the archive of climate model results made for the IPCC fourth assessment report (AR4). The twelve AR4 models used here were chosen because they supplied the necessary data to calculate the SAF using a method developed by Winton (2005b). Details on the twelve models and the SAF analysis method can be found in Winton (2005a).

## II. Method

A zero-dimensional energy balance model allows us to quantify the role of specific forcings and feedbacks in temperature sensitivity. The forcings, $F_i$, and feedbacks, $f_j$, combine to form an expression for the surface air temperature change, $\Delta T$:

$$\Delta T = -\frac{\sum F_i}{\sum f_j} \tag{1}$$

The sign of the $f_i$ corresponds to the sign of the feedback – negative $f_i$ reduce the magnitude of the response. Positive $F_i$ correspond to forcings that increase the temperature response. The forcings and feedbacks together partition the perturbation radiative energy balance at the top of the atmosphere. This energy balance has three components that sum to zero: shortwave, longwave, and net flux. There is some discretion in choosing to interpret a given perturbation flux as a forcing or a feedback – feedbacks are distinguished by having a direct or indirect connection to surface temperature.

The $CO_2$ forcing, $F_{CO2}$, is produced by a separate radiation calculation and provided as a diagnostic in the AR4 archive. The other “forcing”, the net top-of-atmosphere flux, $F_N$, represents the perturbation of the net heat flux through the surface plus the convergence of atmospheric heat transport (since the atmospheric heat content change is negligible):

$$F_N = \Delta S - \Delta OLR \tag{2}$$

where $\Delta S$ is the perturbation top-of-atmosphere shortwave absorption and $\Delta OLR$ is the perturbation outgoing longwave radiation. For the globe there is no perturbation atmospheric heat transport convergence so $F_N$ represents the global surface flux – dominated by ocean heat uptake.

The surface albedo feedback is estimated as:

$$f_{SAF} = \frac{\Delta S_{\alpha \to \alpha'}}{\Delta T} \qquad (3)$$

where $\Delta S_{\alpha->\alpha'}$ represents the change in the top-of atmosphere shortwave due to replacing the control run surface albedo, $\alpha$, with the perturbation run surface albedo, $\alpha'$. The method used for this replacement actually estimates the surface change but this has been shown for the GFDL model to be close to the top-of-atmosphere value (Winton 2005a; Winton 2005b). Unfortunately, the other radiative feedbacks -- temperature, water vapor, and cloud -- cannot be evaluated with standard diagnostics. The standard diagnostics for evaluating the role of clouds, the clear sky radiative fluxes, are not directly useful for calculating the cloud feedback (Soden et al 2004; Soden and Held 2005). The methods for accurately calculating these feedbacks involve specially instrumented runs of the models and/or the model radiation codes (Colman 2003a; Soden and Held 2005). To sidestep this difficulty, we group the feedbacks besides SAF into two composite feedbacks: non-SAF shortwave feedback, and longwave feedback. The non-SAF shortwave feedback contains contributions from clouds and water vapor. The longwave feedback contains contributions from clouds, water vapor and temperature. The non-SAF shortwave feedback and the longwave feedback are defined by:

$$f_{NON-SAF-SW} = \frac{\Delta S}{\Delta T} - f_{SAF} \qquad (4)$$

and

$$f_{LW} = -\frac{F_{CO2} + \Delta OLR}{\Delta T} \qquad (5)$$

respectively.

The Arctic amplification is defined as the ratio of the Arctic and global warming. Using (1) for the global and Arctic regions, the Arctic amplification is related to the forcings and feedbacks in the two regions by:

$$\frac{\Delta T_A}{\Delta T_G} = \frac{\left(F_{CO2} + F_N\right)_A}{\left(F_{CO2} + F_N\right)_G} \frac{\left(f_{SAF} + f_{NON-SAF-SW} + f_{LW}\right)_G}{\left(f_{SAF} + f_{NON-SAF-SW} + f_{LW}\right)_A} \qquad (6)$$

where the subscripts A and G refer to the Arctic and global regions respectively.

# III. Results

We begin by looking at the Arctic amplification of climate change in the 1%/year $CO_2$ increase experiments of the models. Figure 1 shows the model mean warming at $CO_2$ doubling (years 61-80) and its standard deviation for the globe, the Arctic (60N-90N), and a sub-Arctic region (47N-60N) constructed to have the same area as the Arctic region. The Arctic has a warming that is, on average, 1.9 times that of the globe and is much more variable among the models than that of the globe. The ratio of the standard deviation to the mean warming (coefficient of variation), a kind of noise to signal ratio, is 0.32 for the Arctic and 0.22 for the globe. This might reflect the particular difficulty of modeling Arctic climate processes specifically or it might simply reflect the greater variation in model simulations of regional climate change. The sub-Arctic region warming is only slightly amplified over global and has a variability that is intermediate between that of the globe and Arctic. The standard deviation to mean warming ratio is nearly the same for the sub-Arctic and Arctic suggesting that the models encounter roughly the same challenge in simulating climate change in the two regions. The diamonds at the right in Fig. 1 show the Arctic amplifications for the individual models. Eight of the models have very similar amplifications just below 2, two are somewhat higher, and two have very little amplification.

As noted, a special calculation is needed from each model to evaluate $F_{CO2}$, the impact of doubled $CO_2$ on the longwave flux at the tropopause. The stratosphere adjusts rapidly to perturbed $CO_2$ and so, by convention, is not included in the $CO_2$ forcing. Six of the twelve models have provided the doubled $CO_2$ forcing. These are listed in Table 1 for the global and Arctic regions. The direct $CO_2$ forcing is less for the Arctic than for the globe in all of these models. If this were the only difference between the two regions there would be less warming in the Arctic than for the globe. The reason for this has been discussed by Colman (2001) and Pierrehumbert et al (2005). The impact of any infrared absorber on OLR is dependent upon the vertical temperature gradient. In the limit of no gradient, greenhouse absorbers have no impact on OLR. Since the Arctic has a lower vertical temperature gradient than the globe as a whole, a given change in a greenhouse absorber will be less effective there. This effect can also be seen for water vapor in Colman (2001, 2003), Held and Soden (2005) and Pierrehumbert et al (2005), and for cloud fraction in Colman (2003). In winter, when the Arctic vertical temperature gradient is even smaller than the annual mean, the water vapor feedback is especially small and can even become negative (Colman 2001, 2003).

The model mean forcings and feedbacks for global, sub-Arctic and Arctic regions are shown in Table 2. For models that did not report their $CO_2$ forcing, the mean of the six reporting models has been used to distinguish the longwave feedback in the perturbation OLR (eqn. 5). All of the forcings and feedbacks show significant differences between the global and Arctic regions with intermediate values in the sub-Arctic region. As expected the SAF is larger for the Arctic than for the globe. It is perhaps surprising that the SAF for the sub-Arctic region is nearly as large as that of the Arctic. Although the surface albedo change and consequent shortwave change are smaller there than for the Arctic, the temperature change is also smaller (Fig. 1) leading to a similar sensitivity. Differences in net TOA forcing and longwave feedback also contribute to amplification of Arctic climate change. The net TOA forcing is negative for the globe as expected for the transient uptake of heat by the global ocean. Furthermore there is a significant (at the 1%

level) intermodel correlation between the global warmings and downward net fluxes. This might suggest treating this term as a (negative) feedback. However, $F_N$ behaves quite differently in the Arctic. Although the model average Arctic $F_N$ is near zero, there is a wide variation between the models, from -1.0 to 1.6 W/m$^2$. Between the models, the Arctic $F_N$ is nearly uncorrelated with $\Delta T_A$, $\Delta T_G$, and $\Delta T_G$-$\Delta T_A$, discouraging treatment as a feedback. For uniformity, $F_N$ is treated as a forcing in both regions.

To quantify the impact of individual forcings and feedbacks on Arctic amplification we replace each Arctic term with its global counterpart in (6) and note the Arctic amplification that remains when the term is thus neutralized (Table 3, first line). The second line of Table 3 shows the result of performing this neutralization exercise upon the amplification of the Arctic temperature change over that of the sub-Arctic. For these calculations the model mean forcings and feedbacks are used. Due to the nonlinearity of (6), the model mean terms give an Arctic-global amplification that is slightly less than the model mean Arctic amplification: 1.81 vs. 1.9. The largest impact comes from neutralizing the non-SAF-SW term which increases the Arctic amplification to over 6. This result implies that the Arctic-global difference in this feedback strongly opposes Arctic amplification. Even reducing the global feedback by the Arctic-to-global insolation ratio (0.6) before substituting for the Arctic feedback would only bring this number down to 3.6, leaving it as the difference with the largest impact on Arctic amplification. A small increase in amplification comes from neutralizing the $CO_2$ forcing. Neutralizing the longwave feedback or net TOA forcing eliminates Arctic amplification altogether, implying that the Arctic-global differences in these terms strongly favor Arctic amplification. Neutralizing SAF reduces the Arctic amplification but does not eliminate it. The neutralization of factors contributing to Arctic-sub-Arctic amplification show similar effects except that the SAF neutralization has virtually no impact. These results support the interpretation of SAF as a contributor to Arctic amplification but not a dominating influence upon it.

Now we turn to the causes of the differences in the model simulations of Arctic amplification (Fig. 1). Our method for evaluating the impact of an individual forcing or feedback upon a specific model's relative Arctic amplification is similar to that used to evaluate the role of the individual factors in Arctic amplification. We neutralize each forcing or feedback as a source of intermodel variation by replacing both the global and Arctic values by their model mean counterparts in eqn. 6. Performing all such replacements would result in a value of 1.81 (Table 3). We can quantify the impact of the individual effect on the outlying behavior as the degree to which its neutralization moves the model's outlying amplification toward this value. The results of performing this intermodel neutralization procedure for the four outlying models is shown in Table 4. The first low-lying model has the non-SAF shortwave feedback as the dominant contributor to its low amplification with a significant contribution from the net TOA forcing and an opposing (amplification decreasing) effect from the longwave feedback. The second low amplification model has small contributions toward its low amplification from all factors except the longwave feedback. The non-SAF shortwave forcing is the dominant contributor to the high amplification of the third model joined by a significant contribution from the longwave feedback. The two shortwave feedbacks dominate the high amplification of the fourth model. Summarizing, multiple factors contribute to the outlying behavior of the four models but, in each case, the non-SAF shortwave feedback has the largest influence. For both global and Arctic regions this is the feedback with the largest intermodel variation.

The intermodel neutralization procedure was also applied to the eight similarly amplified models. The standard deviation of amplifications was larger for each neutralized effect than for the unmodified amplifications, indicating compensations between the various forcings and feedbacks are contributing to the agreement within this group.

# IV. Conclusions

The analysis of forcings and feedbacks performed in this paper shows that the Arctic amplification arises from a balance of significant differences in all forcings and feedbacks between the Arctic and the globe. The direct $CO_2$ forcing and non-SAF shortwave feedback inhibit Arctic amplification while the net TOA flux forcing, SAF, and longwave feedback favor it. The SAF, while important, is a lesser factor than the net TOA flux forcing and the longwave feedback in promoting Arctic amplification. Comparing the Arctic and sub-Arctic regions (Table 2), SAF is a negligible influence on the substantially greater temperature change in the Arctic. Multiple factors also contribute to the model differences in Arctic amplification with the non-SAF shortwave feedback seemingly the most important.

Since multiple processes contribute to the two composite feedbacks and the net TOA flux forcing, it is difficult to associate the Arctic-global differences with specific features of the atmosphere's $CO_2$ response. For example, there are reasons to expect significant contributions to the Arctic-global longwave feedback difference from cloud, water vapor and temperature feedbacks (Colman 2001, Colman 2003a, Vavrus 2004, Soden and Held 2005). The lapse rate feedback, a component of the temperature feedback, would be expected to favor Arctic amplification as it is generally negative in the tropics and positive in the Arctic. A clearer picture of the mechanisms of Arctic amplification in the models will require application of more refined feedback analysis techniques.

A caveat must be attached to the factor replacement technique employed in this study. The determination of a factor as forcing or feedback and the association of a feedback with a particular temperature change are somewhat arbitrary. The increased $CO_2$ experiment alone is inadequate to distinguish dependencies from co-variation. Idealized "ghost forcing" experiments are needed to accurately formulate the temperature dependencies of the energy balance model parameters.

**Acknowledgments:** The author thanks Tom Delworth and Isaac Held for their helpful comments on the manuscript. The author also acknowledges the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy.

## References

Colman, R., 2003a: A comparison of climate feedbacks in general circulation models, *Climate Dynamics*, **20**, 865—873.

Colman, R, 2003b: Seasonal contributions to climate feedbacks, *Climate Dynamics*, **20**, 825—841.

Colman, R.A., 2001: On the vertical extent of atmospheric feedbacks, *Climate Dynamics*, **17**, 391—405.

Flato, G.M., and CMIP Modelling Groups, 2004: Sea-ice and its response to CO2 forcing as simulated by global climate models, *Climate Dynamics*, **23**, 229—241.

Hall, A., 2004: The role of surface albedo feedback in climate, *J. Climate*, **17**, 1550--1568.

Holland, M.M., and C.M. Bitz, 2003: Polar amplification of climate change in coupled models, *Climate Dynamics*, **21**, 221--232.

Pierrehumbert, R.T., H. Brogniez, and R. Roca, 2005: On the relative humidity of the Earth's atmosphere. In The General Circulation, T. Schneider and A. Sobel, eds., Princeton University Press, to appear.

Soden, B.J., and I.M. Held, 2005: An assessment of climate feedbacks in coupled ocean-atmosphere models, *J. Climate*, submitted.

Soden, B.J., A.J. Broccoli, and R.S. Hemler, 2004: On the use of cloud forcing to estimate cloud feedback, *J. Climate*, **17**, 3661—3665.

Vavrus, S., 2004: The impact of cloud feedbacks on Arctic climate change under greenhouse forcing, *J. Climate*, **17**, 603—615.

Winton, M., 2005a: Surface albedo feedback estimates for the AR4 climate models, *J. Climate*, in press.

Winton, M., 2005b: Simple optical models for diagnosing surface-atmosphere shortwave interactions, *J. Climate*, in press.

## Captions

**Table 1:** Global and Arctic doubled $CO_2$ tropopause level forcing for the six models providing data.

**Table 2:** Model mean forcings and feedbacks: global, sub-Arctic, and Arctic.

**Table 3:** Arctic-amplification with model mean parameters and global to Arctic forcing/feedback replacement (first row) and sub-Arctic to Arctic forcing/feedback replacement (second row).

**Table 4:** Arctic-amplification of four outlying models (two low and two high) when individual effects are neutralized by replacing the given model forcing or feedback with the model mean value. Using all model mean values gives an Arctic amplification of 1.81 (Table 3).

**Figure 1:** Model mean global, sub-Arctic, and Arctic warmings and their standard deviations. Model mean Arctic amplification and its standard deviation are also plotted. The diamonds at right represent the polar amplification values for the individual models.

**Table 1:** Global and Arctic doubled $CO_2$ tropopause level forcing for the six models providing data.

| | $F_{CO2}$ (W/m$^2$) | | |
|---|---|---|---|
| **Model** | **Global** | **Arctic** | **Arctic/Global** |
| GISS MODEL E | 4.21 | 3.20 | 0.76 |
| MIROC 3.2 HIRES | 3.59 | 2.69 | 0.75 |
| MIROC 3.2 MEDRES | 3.66 | 3.21 | 0.88 |
| MPI ECHAM 5 | 3.98 | 3.25 | 0.82 |
| UKMO HADCM3 | 4.03 | 3.12 | 0.78 |
| UKMO HADGEM1 | 4.02 | 3.41 | 0.85 |

**Table 2:** Model mean forcings and feedbacks: global, sub-Arctic, and Arctic.

| | Forcings (W/m$^2$) | | Feedbacks (W/m$^2$/K) | | |
|---|---|---|---|---|---|
| **Region** | $F_{CO2}$ | $F_N$ | $f_{SAF}$ | $f_{NON\text{-}SAF\text{-}SW}$ | $f_{LW}$ |
| Global | 3.92 | -1.22 | 0.29 | 0.56 | -2.45 |
| Sub-Arctic | 3.43 | -0.77 | 0.72 | 0.03 | -2.11 |
| Arctic | 3.15 | 0.07 | 0.75 | -0.20 | -1.61 |

**Table 3:** Arctic-amplification with model mean parameters and global to Arctic forcing/feedback replacement (first row) and sub-Arctic to Arctic forcing/feedback replacement (second row).

| **Neutralized** | none | $F_{CO2}$ | $F_N$ | $f_{SAF}$ | $f_{NON\text{-}SAF\text{-}SW}$ | $f_{LW}$ |
|---|---|---|---|---|---|---|
| $\mathbf{\Delta T_A/\Delta T_G}$ | 1.81 | 2.24 | 1.08 | 1.26 | 6.48 | 1.01 |
| $\mathbf{\Delta T_A/\Delta T_{SA}}$ | 1.56 | 1.70 | 1.15 | 1.52 | 2.00 | 1.06 |

**Table 4:** Arctic-amplification of four outlying models (two low and two high) when individual effects are neutralized by replacing the given model forcing or feedback with the model mean value. Using all model mean values gives an Arctic amplification of 1.81 (Table 3).

| **Neutralized** | none | $F_{CO2}$ | $F_N$ | $f_{SAF}$ | $f_{NON\text{-}SAF\text{-}SW}$ | $f_{LW}$ |
|---|---|---|---|---|---|---|
| Model 1 | 1.13 | 1.13 | 1.34 | 1.18 | 1.65 | 0.78 |
| Model 2 | 1.18 | 1.29 | 1.23 | 1.34 | 1.35 | 1.18 |
| Model 3 | 2.29 | 2.29 | 2.98 | 2.39 | 1.64 | 1.82 |
| Model 4 | 2.41 | 2.28 | 2.75 | 1.97 | 1.91 | 2.31 |

**Figure 1:** Model mean global, sub-Arctic, and Arctic warmings and their standard deviations. Model mean Arctic amplification and its standard deviation are also plotted. The diamonds at right represent the polar amplification values for the individual models.